Comparison of Sensorimotor Coordination in Deaf and Hearing Infants

Research Thesis

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By

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Introduction

Sensorimotor experiences are essential to laying the groundwork for infants' conceptual and motor development. In the first two years of life infants primarily use their senses to learn about the world around them (von Hofsten & Rosander, 2018). Sight, hearing, and movements all play key roles in early cognitive development. Through their actions with objects, infants learn that their actions can cause objects to move in the world around them and that objects exist even when they cannot be seen or felt by the infant (Piaget, 1954). As a child develops cognitive and motor abilities, they begin to be able to understand that their actions can change their environment around them and can move objects to complete simple tasks (Piaget, 1954). These simple tasks act as the foundation for more complex skills later on in a child's development (Philips & Shonkoff, 2000).

The theory of e*mbodied cognition* argues that sensorimotor experiences during early development and later in life are necessary for the acquisition and retention of conceptional knowledge (Wellsby & Pexman, 2014). Therefore, cognition isn't constrained to what happens in our minds. It is also influenced by our interaction with the physical world. Lakoff (2012) argues that primitive cognitive functions that structure abilities such as visual perception, motor action, and mental images are embodied and develop through the interaction of one's body with its environment. This is supported by the integration of neurological pathways for motor tasks such as walking and abstract discourse (Narayanan, 1997). Because of this intrinsic linkage of physical action to cognition, the loss of a sensory modality may, in turn, produce a deficiency in cognition (Castellanos et al., 2018).

The embodied cognition phenomenon is uniquely observable in infants because of the rich period of early cognitive development during infancy (Kontra et al., 2012). It is also been found that infants also learn about their environment around them through multiple sensory modalities. Infants bang objects together to understand sound and mouth them to understand the texture and taste of objects. All the information from these modalities is integrated to form a rich, multimodal representation of the object (Fagan, 2019). In a study by Hayne et al. (2003), it was found that infants who observed actions displayed by a presenter and then were prompted to replicate those actions were better able to recall them six weeks later as opposed to infants who only observed the presenter doing the action. In another study by James & Swain (2011), infants were better able to learn novel verbs after acting on an object as opposed to watching somewhat act on an object. Specifically, infants who performed the action of a novel verb demonstrated a greater neural response in the motor region upon recall of the verb corresponding to that action, showing a link between sensorimotor experience and language. These studies show that infants' cognitive processes are influenced by their motor systems and motor processes. As infants acquire new motor skills, their understanding of the actions they observe also grows, suggesting that perception and action are coupled from the first days of life.

This linkage between the sensory modalities and cognition may allow normally functioning infants to display a stronger development of cognition than infants with compromised modalities (Nagai & Asada, 2015). Multiple studies have revealed that when compared to hearing-impaired children with Cochlear implants (CI), normal hearing (NH) children may show stronger abilities in many fine and general motor skills such as: balance, general dynamic coordination, visual-motor skills, ball catching abilities, and have displayed differences in reaction time and general movement speed (Savelsbergh et al., 1991; Siegel et al., 1991; Wiegersma & Velde, 1983). Balance specifically has been noted as being consistently decreased in deaf young deaf populations and this may be due to auditory deprivation or other aspects of the inner ear and perception of balance (Gheysen et al., 2008). During the period before receiving a CI, the infants are not exposed to high-quality spoken language and in many cases have fewer parent-child interactions that are also generally lower quality due to communication barrier between parent and child (Barker et al., 2009; Meadow-Orlans & Spencer, 1996). Also, deaf infants interact with their environments differently due to the lack of auditory feedback from objects and their actions and therefore have different motor experiences that promote different motor skills (Fagan, 2019). Reinforcing the notion of differing environmental perception, deaf infants also have been found to fixate on objects for a longer amount of time, leading researchers to believe that they take a longer time to familiarize themselves with visual objects and to habituate to them (Monroy et al., 2019). Horn et al. (2006), for example, found that NH infants displayed stronger fine motor skills than their CI counterparts, where time before receiving a CI correlated with the degree of difference in fine motor skills. From these differing behaviors between CI and NH infants, hearing loss provides a unique opportunity to examine the importance of sound for cognitive, social, and linguistic development.

As infants develop these basic functions of cognition and motor skills, infants also develop the ability to coordinate these actions with another individual in a joint interaction. A joint interaction is any interaction between two or more individuals in which the individuals must coordinate their actions to produce a sought-after result, and how effectively the individuals can complete this task relies on all parties' joint coordination (Sebanz et al., 2006). Even during the first weeks after birth infants and parents make communicative exchanges that connect them with their baby. The quality of these interactions builds the foundation for development in social skills and joint coordination, and low-quality interactions between parent and child can lead to language and attentional problems (Barker et al., 2009). These early interactions with parents lay the foundation for subsequent more advanced interactions later in life, in a way that infants are involved in facilitating their own cognitive and social development (Bornstein, 2002). Rich interactions between a parent and child can improve the rate of development and strengthen cognition, social development, and language development. However, poorer-quality parent-child interactions can cause this principal development period to be delayed causing developmental setbacks in young infants (Rocha et al., 2020). Kaur et al. (2018) has also found a correlation between motor performance and interpersonal motor synchrony in children with ASD showing a linkage between motor synchrony during a task and motor proficiency.

The parent-child relationship provides a crucial context for learning during infancy. For example, infants gain information on many social-cognitive processes including verbal and non-verbal communication, gaze following, and emotion recognition and regulation (Iarocci & Gardiner, 2015). An important type of early interaction an infant has with a parent is parent-child play. Through play, infants learn about themselves, their environment, and how to effectively interact with others socially, leading to better social skills during youth. Rich physical play between parents and children is linked to better social skills in adolescence (MacDonald & Parke, 1984). This may be due to physical play with parents allowing infants to understand both their role in social interactions as well as their partner's role and complete these interactions efficiently.

Examining parent-child joint play sessions allows us to witness at what level an infant understands actions they are involved in and at what level they can proficiently understand and complete joint tasks. The successful and efficient completion of a joint parent-infant task requires both motor coordination as well as action planning (Adolf & Franchak, 2017).

Successful joint tasks rely on both individuals being able to think through and predict their actions (action planning) as well as their partners (action prediction; Sebanz et al., 2006). Infants have to coordinate eye and hand movements while understanding their role in the dyad as well as their partner's role. The link between sensorimotor development and cognitive development, increases in motor skill development can also stimulate development in higher-order cognitive skills not yet acquired (Van der Fels et al., 2014). Children with less developed motor skills may perform poorly in joint interactions which could contribute an impairment to social interactions and other interactions that require cooperation between multiple individuals (Fulceri et al., 2018).

The Current Study

This study attempts to determine if there is a link between prelingual deafness and cognitive delays based on lower-quality sensorimotor experiences attributed to that deafness. We recorded and collected eye-movement data for deaf infants completing a joint task with a parent that included picking up an object, passing that object to the other member of the dyad, and the second member moving the object to a goal location. This all took place in a play-type environment that resembled a natural interaction between parent and infant. We then compared the ability to complete these tasks with age-matched infants with normal hearing. We quantified the infant's anticipatory gaze of parent actions, synchrony during joint interactions, and the infant's proficiency at completing the goal of the joint task. In this study, three metrics were recorded and analyzed to quantify an infant's efficiency of a joint task.

The first metric examined in this study is action prediction. Action prediction during a joint task is an indicator of action understanding because the infant can successfully be able to predict their partner's actions (Hunnius & Bekkering, 2014). Action prediction can be quantified by tracking anticipatory gaze of their partner's movements. Being able to move one's eyes, head, and body simultaneously in a planned and coordinated manner is a great accomplishment in itself, and one that takes much practice. Being able to link that to action anticipation shows rich cognitive development and integration in an infant (Biro, 2013). Action prediction in infants also requires knowledge of the task to predict future events of that task (Monroy et al., 2017).

The second metric is synchrony between parent and child. Synchrony measures how consistent the parent and child are with their movements and is an indicator of planning actions and understanding of the task at hand. Infants have an innate somatosensory response that creates a distinct relationship with their mother. This bond leads to the formation of a coordinated relationship between the two because of the heightened sense for each other's actions (Fleming et al., 1999). This synchrony in early interactions between parent and infant can supplement neuroendocrine pathways that are associated with long-term expression and emotion (Feldman, 2012). In the current study, parents and infants exchange objects from one person to another. A simple reach for an object in the parent's hand shows an infant has the understanding of the object, its location, the location of their hand, as well as the conceptual understanding the reaching motion may result in them obtaining the target object. An infant that reaches for an object at the appropriate moment their parent is passing it to them displays understanding their role in the interaction and the ability to work together to complete the task (Meyer et al., 2016). Synchrony has been used as a measure in joint coordination tasks by Fulceri et al. (2019) to examine how children with autism spectrum disorder coordinate their movements with others in a joint task as compared to typically developing children. Adding synchrony as a variable allows for the quantification of how well the infant understands the interaction. Synchrony is also an indicator of parent-child familiarity, rich cognitive development, and has been linked to more positive child behavior outcomes (Leclère et al., 2014).

The third metric is the proficiency of movements of the child. Motor skills begin developing immediately after birth and continue to develop during the entire life span (Adolf & Franchak, 2017). A child who is proficient in manipulating objects shows development in motor control. The development of the motor system is highly integrated and is affected by other sensory modalities (Smith & Gasser, 2005). Successful motor control relies on many basic factors including generating physical movement, controlling that movement, and managing those forces through biomechanical systems (von Hofsten, 1983; Thelen, 1985). It also relies on higher-order systems including perception and cognition that govern how that motor movement is planned out and the goal is accomplished (von Hofsten, 2004). Sensorimotor coordination in infants is a well-studied phenomenon (Yu & Smith, 2013; Yu & Smith, 2017), but there is little research on sensorimotor coordination for infants with hearing loss.

It remains unclear why CI infants display different motor behavior than NH infants. This study supports the idea that because of embodied cognition, sensory stimulus plays an integral role in cognitive development. It aims to examine the possible discrepancy in cognitive development in CI infants because of the reduced amount of high-quality sensory information. In contrast, CI infants may not display discrepancies in skills needed during a joint interaction. This could occur due to the child being able to make up for the congenital loss in hearing by obtaining rich sensorimotor information about their surroundings through their other modalities. Given the previous research on this topic, I predict that the CI infants will show differences in action prediction, motor synchrony, and motor proficiency.

Method

Participants

The sample of participants was drawn from a longitudinal study at The Ohio State University by Claire Monroy and Derek Houston investigating parent-child interactions of deaf infants with cochlear implants using head-mounted eye-tracking. Twelve parent-child dyads participated in this study: six infants with cochlear implants and six infants with normal hearing who were matched to CI subjects based on age. CI subjects were recruited from Nationwide Children's Hospital.

CI Group

The CI infants' (n=6) ages ranged from 13.97 months to 20.8 months (average=17.86, SD=2.66) on the day of testing. These infants had an average of 7.62 months (SD=2.58) of hearing experience after CI implantation. Of these six infants, three were female. All participants had bilateral, severe-to-profound sensorineural loss and were implanted in both ears.

Normal Hearing, Chronological Age Matched (NH-CAM) Group

The infants with CIs were age-matched to six normal hearing subjects (two females). The NH group ages ranged from 14.27 months to 24.97 months (average=19.18, SD=3.62) on the day of testing.

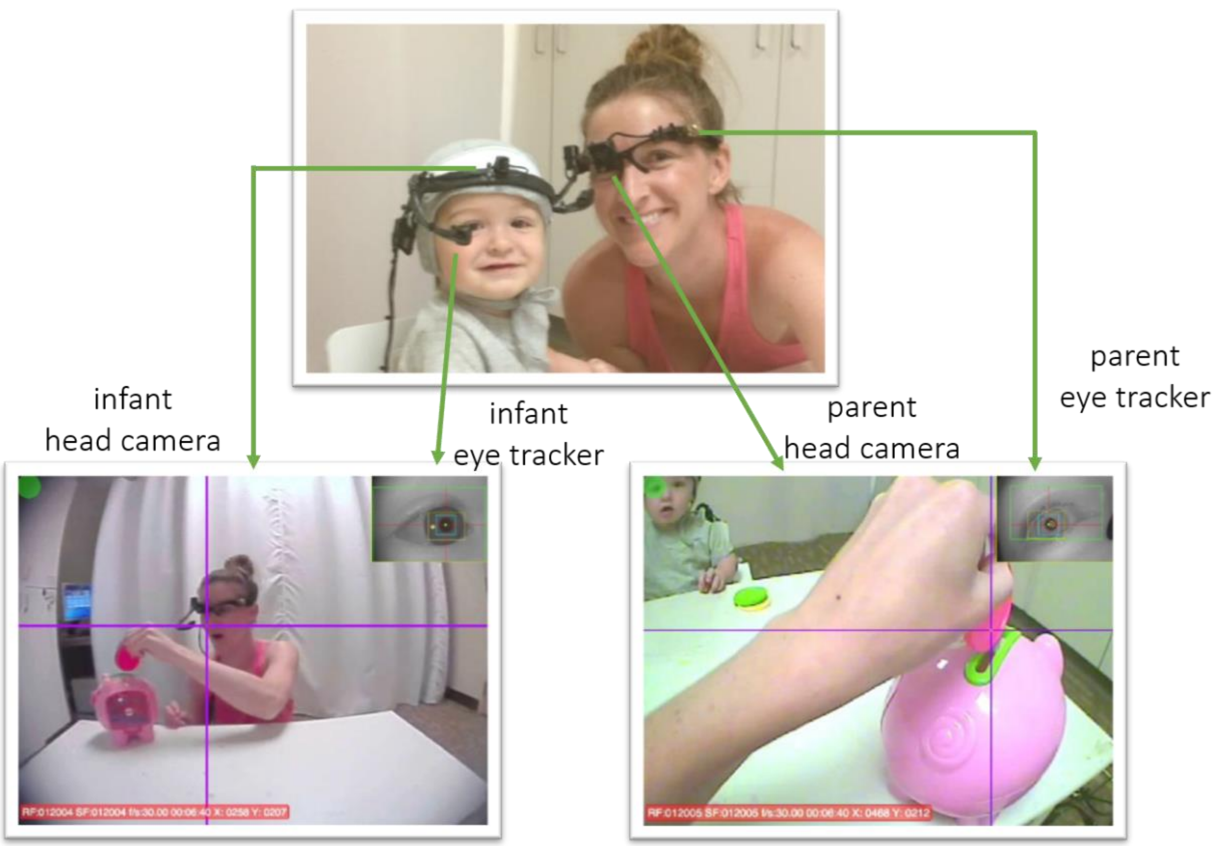
Procedure

This data was collected by conducting a 'real-world' play session between an infant and parent. The dyad was brought to the lab where the play session experiment was set up and the dyad was asked to complete a task together in a similar manner of at-home play.

Equipment Setup

Both parent and infant wore eye-tracking cameras (Figure 1). The eye tracker used one camera to track the position of the individual's pupil and an infrared camera tracked the location of the corneal reflection to obtain accurate gaze data. Scene cameras that captured the individual's point of view were also mounted on the head cap of the participant. Cameras were then set up to capture third-person perspectives of both participants and an aerial view camera also captures the play session from above. To calibrate the eye-tracking equipment, a laser pointer was flashed onto a piece of black cardboard to ensure gaze direction was being correctly measured during coding.

Figure 1. Head-mounted eye-tracking equipment



Parent-Child Play Session

The play session experiment consisted of two rounds. In the first round, the parent was given a stack of ten large plastic coins and the infant was given a piggy bank. The parent was then instructed to pass the coins to the infant one by one for the infant to place inside the piggy bank. The parent was also instructed to interact with the infant in a way they normally would during play. Once all ten coins had been placed in the piggy bank, the coins were taken out and the roles were reversed. The parent was given the empty piggy bank, and the child was given the stack of ten coins. During this round, the child passed coins to their parent one-by-one and the parent took the coins from the infant and placed them into the piggy bank. The second round was complete when all coins were placed into the piggy bank by the parent. After the second round was completed, the experiment is finished.

Coding Scheme

To best assess the infant's behavior during this experiment, we conducted frame-by-frame coding analysis of the infant's gaze direction and hand activity during the action phase of the task. To code gaze data, gaze direction (based on pupil position and corneal reflection position) was superimposed on the first-person video recording of that individual. To code gaze direction, each frame of video from the experiment was coded based on which region of interest (ROI) the infant was focusing their gaze toward (Table 1).

Table 1. Behavioral Coding Scheme of Gaze

Region of Interest (ROI)	**Description**

Target Coin	When the subject is looking at the next coin that is put in the goal from that individual's perspective. Based on this definition there can be two simultaneous target coins in some cases, such as the parent moving the "target coin" that they were handed by the infant toward the piggy bank to be put in the goal and the child reaching for a new "target coin" before the first coin has been placed into the piggy bank by the parent member of the dyad.
Non-target Coin	When the subject is looking at a coin that is not the target coin.
Goal	When the subject is looking at the slot section of the piggy bank, where the target coin is to be placed into.
Partner Hand	When the subject is looking at the hand of the other individual of the dyad.
Partner Face	When the subject is looking at the face of the other individual in the dyad.
Other	When the subject is not looking at any of the specified ROI's or when gaze direction is unknown.

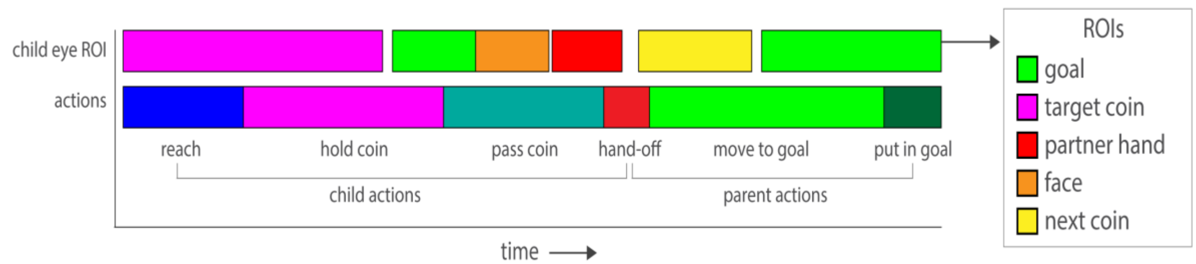
To code the action phase of the parent-child interaction a similar approach was taken. ROI's that the infant could touch during the action phase were defined, as well as specific movements the infant's hand must make to complete the task successfully. Data was coded on a frame-by-frame basis for each hand individually. This coding scheme gave each frame a recorded value for each hand (Table 2). The Left and right hands of each individual were coded separately and then merged with gaze data for integrated analysis of the parent-child interaction (Figure 2).

Table 2. Behavioral Coding Scheme of Hands

Region of interest (ROI)	**Description**

Target Coin	When the hand is holding the next coin that is put in the goal from that individual's perspective. Based on this definition there can be two simultaneous target coins in some cases, such as the parent moving the "target coin" that they were handed by the infant toward the piggy bank to be put in the goal and the child holding a new "target coin" before the first coin has been placed into the piggy bank by the parent member of the dyad.
Non-target Coin	When the hand is touching a coin that is not the target coin.
Reaching	When the hand is moving towards the target coin. This action must be followed by the holding of the target coin by the individual.
Passing	When the hand holding the target coin is moving towards their partner. This action must be followed by the exchange of the target coin.
Handoff	When both members of the dyad are touching the target coin at the same time.
Moving Coin	When the hand holding the target coin is moving the target coin towards the goal location.
Goal	When the target coin is simultaneously in the hand of the subject and also touching the goal location.
Other	Any other hand position not previously stated or when hand location is unknown.

Figure 2. Example coding of parent-child interaction



Note. This example shows round 2 where the infant passes the coin to the parent.

Trial Coding

To accurately gauge the specific moments of the interaction such as the hand-off phase and putting the target coin into the goal phase, the second set of coding was done. This coding broke down interactions by trial. Each trial began with one subject reaching to pick up the target coin and the other subject releasing the target coin into the goal. Each trial was labeled as a successful interaction where the coin was passed and put into the goal or a failure. The reasoning for failure was specified (ex. Parent put the coin into the goal for child). Peer support was also specified in instances where the child could not fulfill the task alone, and the parent intervened by helping the infant.

Dependent Measures

After frame-by-frame coding the video recordings, we used the resulting data to calculate our primary dependent measures of synchrony, action prediction, and proficiency.

Action Prediction

Action prediction was coded in two ways during the task. Action prediction of the parent was defined as instances of the infant looking at the target location within three seconds of the parent putting the target coin into the goal location. It is calculated by subtracting the moment the coin is inserted in the goal by the parent from the moment the child looks to the goal. Action prediction of self is coded as instances of the infants looking at the target within three seconds putting the target coin into the goal themselves. The value is calculated as the initiation of the coin in the goal time frame subtracted by the initiation of the looking at the goal time frame.

Motor Synchrony

Following the procedure of Fulceri et al., (2018), we defined synchrony as the difference in the initiation of reaching for an object of an experimenter and subject. Synchrony was calculated in both rounds during the passing coin phase of each interaction. In the first round it was calculated by taking the absolute value of the difference between when the parent beings to pass the coin and the infant begins to reach for the coin followed by the handoff period. In the second round, synchrony is coded in the same way, except using the infant passing coin and the parent reaching for coin data. Synchrony is an effective measure of the subjects understanding of their role as well as their parent's role in the parent-child joint task and the integration of cognition and motor action because it integrates action prediction of the partner's movements and subsequent motor action in response to that prediction that aids in the successful completion of the task.

Motor Proficiency

Motor Proficiency was a measure of how well the infants were able to put the target coin into the goal location without the assistance of the parent. It was calculated by the offset of the child successfully putting the coin into the goal location subtracted by the onset. If multiple attempts by the infant were necessary, the total insertion time of all attempts was used for this measure. For example, if the infant took two separate attempts to successfully drop the coin into the goal, the two periods of time where the coin was touching the goal were summed together to calculate total insertion time. In order to balance the number of successful instances where the infant was able to put the coin into the goal unassisted and the time it took the infants to put the coin into the goal net score was calculated (Equation 1).

Equation 1. Net Score of proficiency

$$\text{Net score} = \sum_{n=1} \left(\frac{1}{T_n} + 1\right).$$

In equation 1, T = total insertion time and n = successful proficiency trial. Using this equation, infants with a higher score were considered as having better motor proficiency than those with a lower score. For a trial that did not result in a successful insertion of the coin into the goal location, the infant was given a score of zero for that trail. An infant who was not able to put the coin into the goal at all during the experiment was given a net score of zero. Parent intervention was also controlled for this interaction. Any time the parent intervened during the infant attempting to put the coin in the goal (i.e., guiding the infant's hand to the goal by touching their hand, holding the piggy bank to make it easier for the infant to put the coin in, or put the coin in the goal for the infant) that trial was scored as a zero. The scores of all trials were summed to calculate the net score during the task.

Reliability Coding

When coding eye gaze data, a secondary coder recorded a random 30% of participants used in this study. Disagreements longer than 10 frames (0.33 seconds) between coders were resolved via discussion; therefore, interrater reliability was 96%. When coding data for the participant's hand movements, a secondary coder coded a random 20% of participants in this study. Interrater reliability ranged from 93% - 96% for in-hand-coding.

Results

Values of mean data for all measures for both groups are shown in Table 3. A Pearson's correlation test was used for each measure taken during this study (i.e., infant action prediction of the parent, infants prediction of self, synchrony during round 1, synchrony during round 2, infant proficiency) to test whether the age of the subjects correlated with performance of measures. All correlations were found to be non-significant (all $p > 0.149$).

Table 3

Group Values for Data Measures Extracted from Recording of Parent-Child Interaction

	Group	N	Mean	SD
Age (months)	CI	6	17.857	2.662
	NH	6	19.178	3.621
Length of prediction for own action (seconds)	CI	6	0.345	0.266
	NH	6	1.107	2.236
Synchrony of passing coin (parent to infant)	CI	6	1.713	1.389
	NH	6	1.712	1.440
Synchrony of passing coin (infant to parent)	CI	6	1.322	0.920
	NH	3	0.573	0.093
Length of prediction of parent action (seconds)	CI	4	1.181	0.580
	NH	5	0.862	0.817
Proficiency Weighted Score	CI	5	6.451	5.471
	NH	3	7.811	8.806

Note. N<6 when subjects are not able to display the measured activity during the play session

Mann-Whitney independent sample t-tests were used to test whether there were differences between deaf and hearing groups for each dependent measure. These tests revealed no significant differences in the two groups for all measures tested (all $p>0.166$). This data, therefore, shows no difference in prediction of a parent's action, prediction of one's action, synchronizing actions with a parent, and motor proficiency between the CI infants and the NH infants.

Action Prediction of Parent

No statistical significance was found between the CI and NH groups (figure 3) based on the anticipatory period between them looking at the goal and the subsequent placing of the coin into the goal by the parent ($p = 0.556$). The CI group displayed on average a slightly faster prediction time for the infants who were able to predict the actions of their parent (NH mean= 0.862, SD=0.817; CI mean=1.181, SD=0.580). However, out of the six participants for each group more, NH participants were able to successfully predict the actions of their partner putting the coin into the goal (NH n=5; CI n=4). This is displayed in figure 4, showing how many participants were able to display the behavior of each measure.

Figure 3: Comparison of latency in anticipation between groups

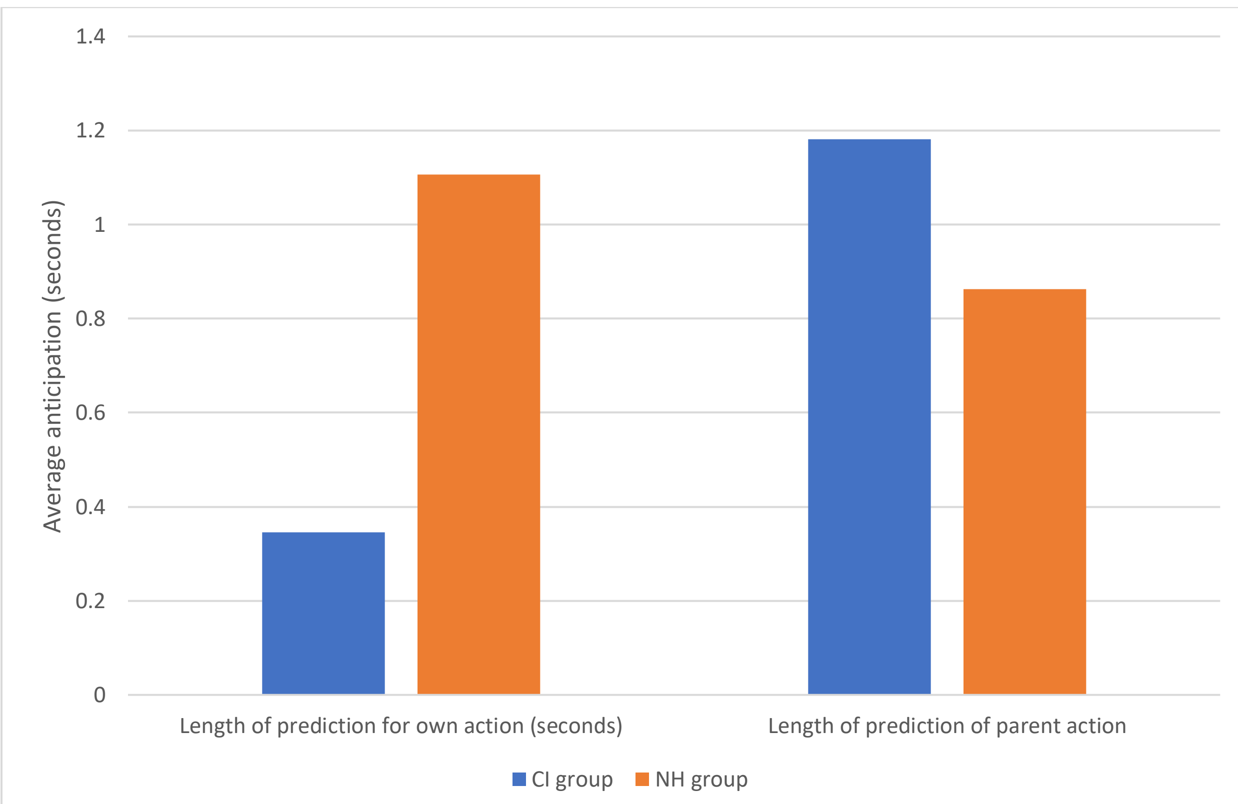
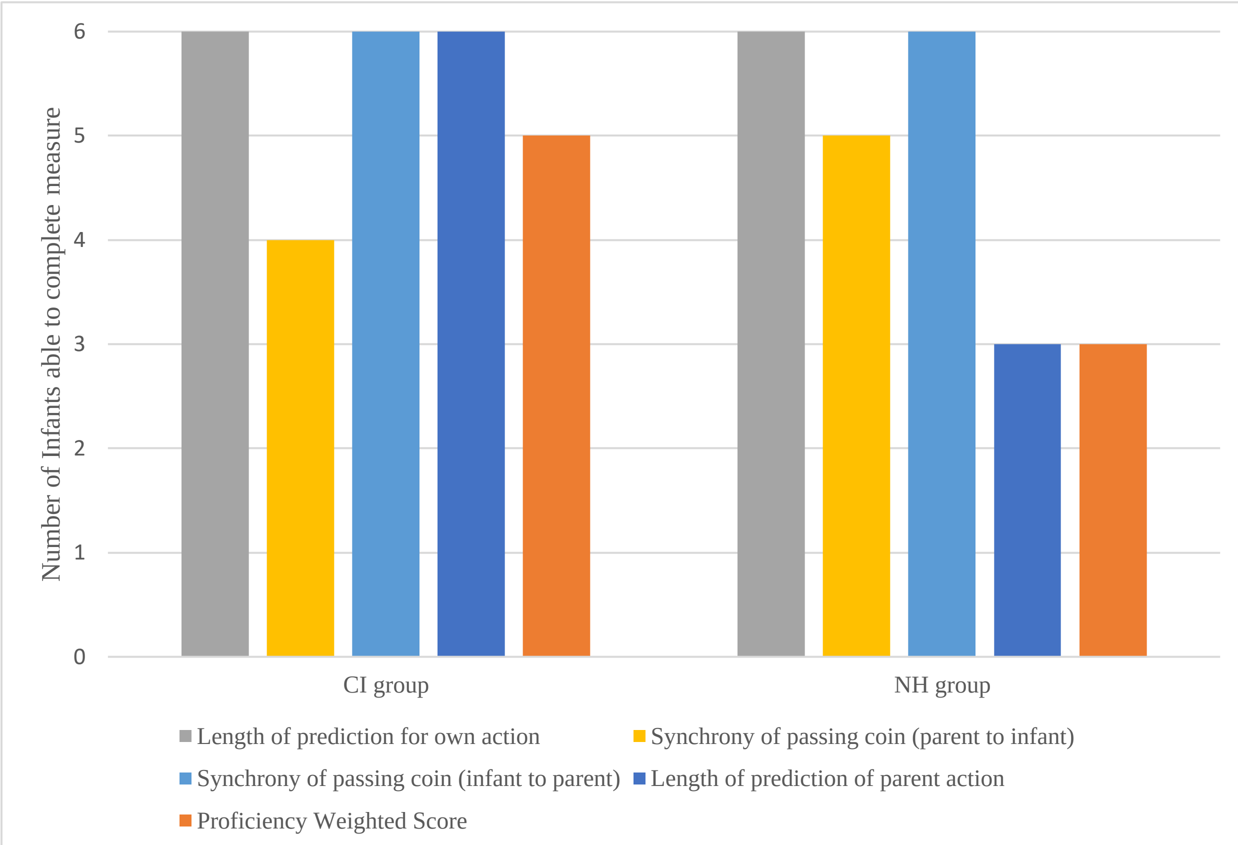


Figure 4: Presence of Measured Behaviors in Both Groups



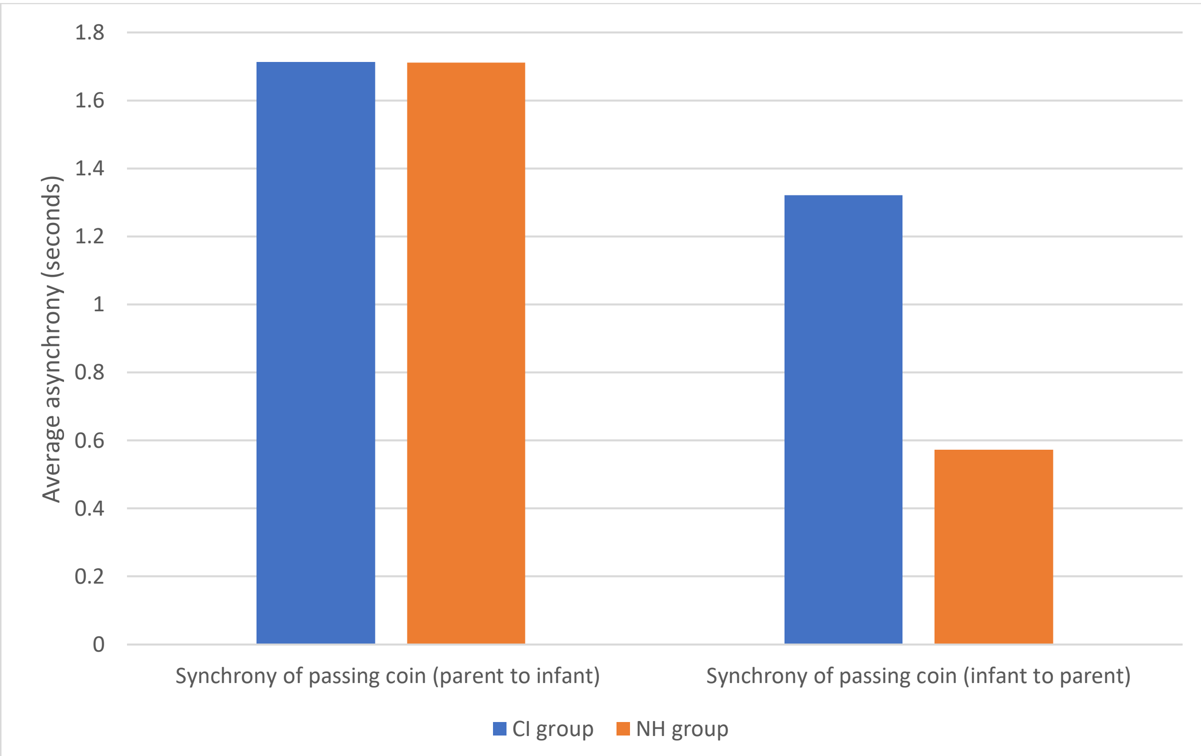
Action Prediction of Self

No statistical significance was found between the CI and NH groups based on the anticipatory period between their predictive gaze and subsequent action at the goal location ($p=0.937$). The NH infants were on average able to predict their actions sooner (NH mean=1.107, SD=2.236; CI mean=0.345, SD=0.266). All participants were able to predict their own action at least once.

Synchrony

When the parent was passing the coin to the infant, there was no significant difference in synchrony of movements for the NH and CI groups ($p=0.699$; figure 5). The average asynchrony of these interactions was near identical for both groups (NH mean=1.712, SD=1.440; CI mean=1.713, SD=1.389). All infant/parent dyads were able to complete at least one successful hand-off when the parent was passing the coin.

Figure 5: Comparison of synchrony between groups

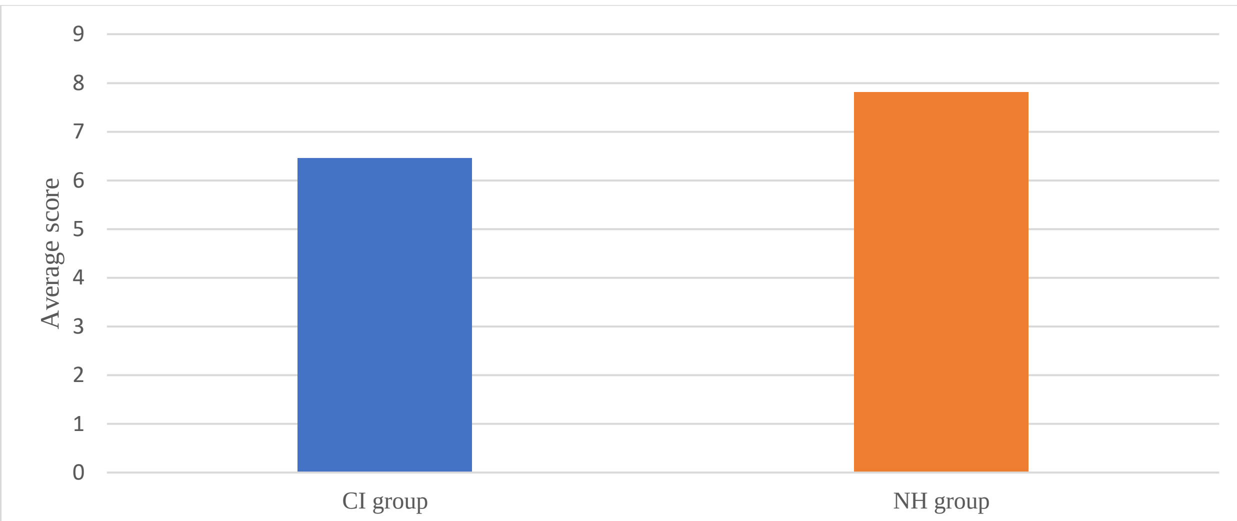


When the infant was passing the coin to the parent, there was also no significant difference between groups ($p=0.167$). The average asynchrony of these interactions was slightly higher for the CI group (NH mean=0.573, SD=0.093; CI mean=1.322, SD=0.920). However, when the infant was passing the coin to the parent, not all the NH infants were able to make a successful pass to the parent (NH n=3; CI n=6).

Proficiency

When testing the proficiency of the infant putting the target coin into the goal after receiving it from their parent (figure 6), it was found that there was no significant difference between the two groups (p=1.000). The average score was slightly higher for the NH group (NH mean=7.811, SD=8.806; CI mean=6.451, SD=5.471). However, more CI infants were able to put a coin in the goal location without parent intervention (NH n=3; CI n=5).

Figure 6: Comparison of motor proficiency between groups



Discussion

This study attempted to determine if there was a link between prelingual deafness and differences in cognitive development, based on altered sensorimotor experiences attributed to that deafness. This was done by recreating a natural parent-child play environment and using head-mounted eye-tracking technology and video recording to track eye and body movements in a joint task interaction between parent and infant. Hearing infants were used as a comparison group to examine if the CI infants differed from those with normal hearing development. I hypothesized that the sensorimotor skills of the CI infants would be diminished due to their hearing loss and therefore not show as strong performance on the joint task with a parent.

The hypothesis stated was not greatly supported by the data collected in this experiment. The CI infants showed minor discrepancies from the NH group in the prediction of parent's actions, prediction of own actions, synchrony when passing the target coin to the parent, and their proficiency score. These results show that CI infants can develop action skills similarly to their peers.

After analyzing the data from the prediction of the parent aspect of the task, the differences were very slight. The data showed, at most, minor delays in action prediction skills of the CI infants tested. Not every infant was able to successfully anticipate their parent, which complicated the results. 5/6 of the CI infants and only 4/6 of the NH infants were able to make at least one successful prediction of their parent during the joint task. This shows that although more CI infants were able to make predictions of their parents' actions, the NH infants who did predict, predicted earlier on average.

Prediction of one's own actions showed similar results as the predictions of the parent's actions. The CI infants predicted their own movements slightly slower on average but not enough to report significant differences between the two groups. All participants were able to predict their own action of putting the coin into the goal at least once. It has been found that parents vary in communication skills with deaf infants (Beatrijs, 2019). It is possible that the lack of highly effective communication skills in some parents of deaf children can hinder how well the infant understands the task and the roles of each member. Parents of deaf children who can communicate very well with their infants may be able to work through the task at an equitable efficiency to a dyad of NH individuals.

Synchrony in coin passing was nearly identical between groups for the first round when the parent passed the coin to the infant. This shows that during this phase of the interaction infants in both groups seemed to have a similar understanding of the task and ability to attend to their parent's actions while planning and initiating their own reaching action at the appropriate time. Infants likely pass many objects to parents when asked to in normal play, and the results show regardless of hearing status infants can perform this action consistently.

During the second round of the coin passing task, where the infant passed the coin to the parent, the performance of the two groups diverged. The CI infant group showed some improvement throughout the brief experimental session, as their mean synchrony of movements with their parents improved slightly and all were able to synchronize their movements with their parents at least once, which is consistent with their performance in the first round. The NH group showed more varied results. Only half the infants were able to synchronize their movements with their parent and pass the coin effectively. Those who were able to do so did it very effectively; as a result, the average synchrony of this group was low (i.e., less time between parent and infant reach onset). Indicators of more advanced synchrony indicate a higher degree of integration of cognitive ability and motor ability. These data may show that CI infants can show a greater ability to understand complex tasks in general, but the mechanisms of understanding may be slower. This may be due to the CI infants having to often adapt their methods of understanding and communication due to their loss of modality. Conversely, the NH infants may not be as open to understanding complex tasks and will not adapt as well to new interactive contexts. Proficiency data also supports this claim, as again more CI infants were able to manipulate the coin into the target location, while only very efficient NH infants were able to complete that section of the task without parental assistance.

An alternate rationale for this result could be that CI infants are more attuned to pay attention to their parent's visual cues. Deaf infants exposed to sign language have been found to pay greater attention to deaf parents' motor movements (Brooks, 2020). While none of the parents involved in this study were deaf, the hearing parents could be likely to integrate hand motions and signals more often with communication with their CI infant (Gabouer et al., 2018). Iverson et al. (2006) also found that mothers provided more deictic gestures to children with Down syndrome than to typically developing infants, which further supports that mothers may provide more nonverbal cues according to the child's overall developmental level.

The proficiency score also implies that in this test, the NH infants on average only displayed marginally greater motor coordination than the CI infants. This could mean that even though the CI infants had no access to hearing before being implanted, they were able to accommodate and still learn about their environment, just in different ways. Fagan (2019) reported these findings that deaf infants manipulate objects differently to obtain more non-auditory information about them. All the explanations discussed would be consistent with the theory of embodied cognition (Wellsby & Pexman, 2014). Even though the CI infants do not have the same experience with auditory stimuli as the NH infants, it is possible that a combination of both infant and parent behaviors experienced during the infants' development has compensated for this and allowed a rich multimodal experience for the infant.

This study did face some limitations. At times, infants were not cooperative when wearing eye-tracking gear, leading to difficultly discerning gaze location in a small number of cases. Also, each group only consisted of 6 participants. While a large amount of data was able to be collected from each participant, the study would benefit from a larger group of participants to determine whether the lack of differences demonstrated in both deaf and hearing groups remains consistent with more toddlers included in the analyses.

Despite these limitations, the findings reveal important information from a novel data collection technique that creates a natural environment to collect rich data about infant behaviors. The CI infants showed comparable results in all aspects of the coin passing task, showing that despite the period of auditory deprivation in the first few months of life, they were still able to display cognitive development at the same rate as a NH individual. This likely due to infants adapting to life without hearing by using other modalities more. This is supported by the improved adaptability to complex situations that the CI infants displayed during the task. However, this adaptability can likely be attributed to both infant and parent. In future studies, it would be beneficial to examine the parent's behavior as well as the child's. Testing how the parent completes the task could show whether parents of infants with CIs communicate differently or show greater adaptability with their CI infants when partaking in joint action tasks.

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